Star Production by Negative μ-Mesons in a Silver Chloride Crystal*

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(Received June 16, 1949)

A silver chloride crystal has been used to detect μ-mesons which stop in the crystal or in some brass immediately below it. It is found that such mesons and their decay electrons produce pulses well above noise and with rise times of 0.2 to 0.35 μ-sec. On the basis of 79 decay events, the meson mean life is found to be 1.9 ± 0.3 μ-sec. By comparing the pulse height distribution for stopped mesons with the distribution for the hard cosmic-ray component, it is shown that the crystal response is proportional to energy loss for slow, heavily ionizing particles. During an experimental run 263 mesons stop. Forty are observed to decay, and it is calculated that 78 are negative mesons which stop in the crystal. It is first shown that, in general, nuclear capture of negative μ-mesons does not result in the production of stars in which the charged particles carry on the average half the meson rest energy. Further analysis shows that, if stars are produced, the average energy of the charged particles is but a very few Mev, probably less than 3 Mev. Five large pulses associated with stopped particles might be interpreted as star pulses, but some of these may be due to stopped protons.

I. INTRODUCTION

It has been shown by van Heerden that single, fast particles can produce detectable pulses in a silver chloride crystal and that the pulse amplitudes due to β-rays are a measure of the energy which the particles expend in the crystal.[1] We describe here the use of AgCl crystals in investigating star production by negative μ-mesons.[2] A nucleus, when it captures a meson, is excited and may give rise to a star. Our experimental arrangement permits a measurement of the energy of the charged particles in the star, if such particles exist.

When the present experiment was begun, not much was known about the fate of negative mesons. Later, O. Piccioni cited evidence indicating that it is unlikely that captured negative mesons result in stars containing charged particles of appreciable energy.[3] Recent results, obtained using thin foils in a cloud chamber, also indicate little or no such star production.[4] Lattes and Gardner,[5] using photo-plates, first reported some evidence for weak stars from μ-mesons, but recent reports from Berkeley based on more extensive observations reverse this conclusion. On the assumption that the negative μ-meson results in a charge exchange reaction with the nucleus with the emission of a neutral particle (neutrino), J. Tiomno and J. A. Wheeler[6] have calculated for various models the resultant distribution of nuclear excitation energy and conclude that for most reactions the excitation is too low for the emission of even one proton. For heavy elements neutrons would be expected and have been observed by Sard *et al.*[7]

Two other problems concerning the crystal itself will be discussed. The first is the investigation of the use of the crystal in making relative time measurements in the microsecond region. The second is the investigation of the relation which exists between pulse amplitude and the energy expended in the crystal by a particle. The investigation has been restricted to slow, heavy particles near the end of their range and ionizing well above the minimum ionization.[8]

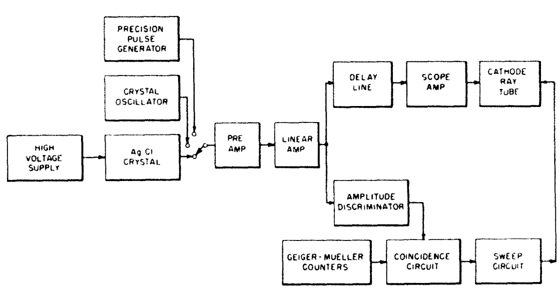

FIG. 1. Block diagram of meson detection system.

II. EXPERIMENTAL ARRANGEMENT

The events of interest to us are those in which a meson of the natural cosmic radiation stops in the crystal or immediately below it, arriving from above within a prescribed solid angle. The meson as it moves through the crystal releases conduction electrons which, under the influence of an applied electric field, move toward the anode, giving rise to a transient current and producing a pulse. The discharge of Geiger-Mueller counters above the crystal simultaneously with the appearance of a crystal pulse indicates the arrival of a particle, and the absence of a discharge in the G-M counters below the crystal indicates the stopping of the particle. The block diagram of Fig. 1 shows the method of correlating the counter and crystal pulses. The crystal signal is amplified, using an amplifier with a

* This work was supported by the Joint Program of the ONR and the AEC; it is based in part on the Doctoral Thesis of one of the authors (H.G.V.).
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1 P. J. van Heerden, Dissertation (Utrecht 1945).
2 Unless stated otherwise, a meson is understood to be a μ-meson.
3 O. Piccioni, Phys. Rev. **73**, 411 (1948).
4 W. Y. Chang, Rev. Mod. Phys. **21**, 166 (1949). R. L. Cool *et al.*, Phys. Rev. **75**, 1275 (1949).
5 C. Lattes and E. Gardner, Phys. Rev. **74**, 1236A (1948).
6 J. Tiomno and J. A. Wheeler, Rev. Mod. Phys. **21**, 153 (1949).
7 Sard, Ittner, Conforto, and Crouch, Phys. Rev. **74**, 97 (1948).
8 W. L. Whittemore, Phys. Rev. **76**, 170A (1949) and Thesis (Harvard Univ. 1949), has investigated crystal response to fast mesons ionizing at or near the minimum rate.

pulse rise time of 0.15 μsec., and is fed to an amplitude discriminator and, simultaneously, to a delay line. If the pulse is large enough, the discriminator operates and transmits a signal to the coincidence circuit. This circuit in turn generates a trigger which starts the cathode ray tube (*CRT*) sweep, provided the proper G-M counter discharges have occurred. Meanwhile, the crystal signal has been delayed by 36 inches of delay line;[9] it appears on the *CRT*, delayed with respect to the beginning of the sweep, and is photographed. A precision pulse generator provides a pulse height calibration, and a 1.6 Mc/sec. quartz crystal oscillator provides a time calibration of the sweep. A pulse shaping line in the linear amplifier makes the crystal pulses 0.7 μsec. wide.[10]

The AgCl crystal, obtained from the Harshaw Chemical Company, has dimensions $3.0\times1.3\times0.25$ inches and is used with an applied field of 2400 volts/cm.[11] Thin layers of silver, developed on the two large surfaces (over an area 1.88×1.13 square inches), form electrodes. The upper (signal) electrode is made negative with respect to the lower (ground) electrode. During experimental observations the crystal's temperature is maintained at 77°K by placing the crystal on a horizontal, silver plated brass cooling plate in an evacuated light-tight box; the plate is in contact with

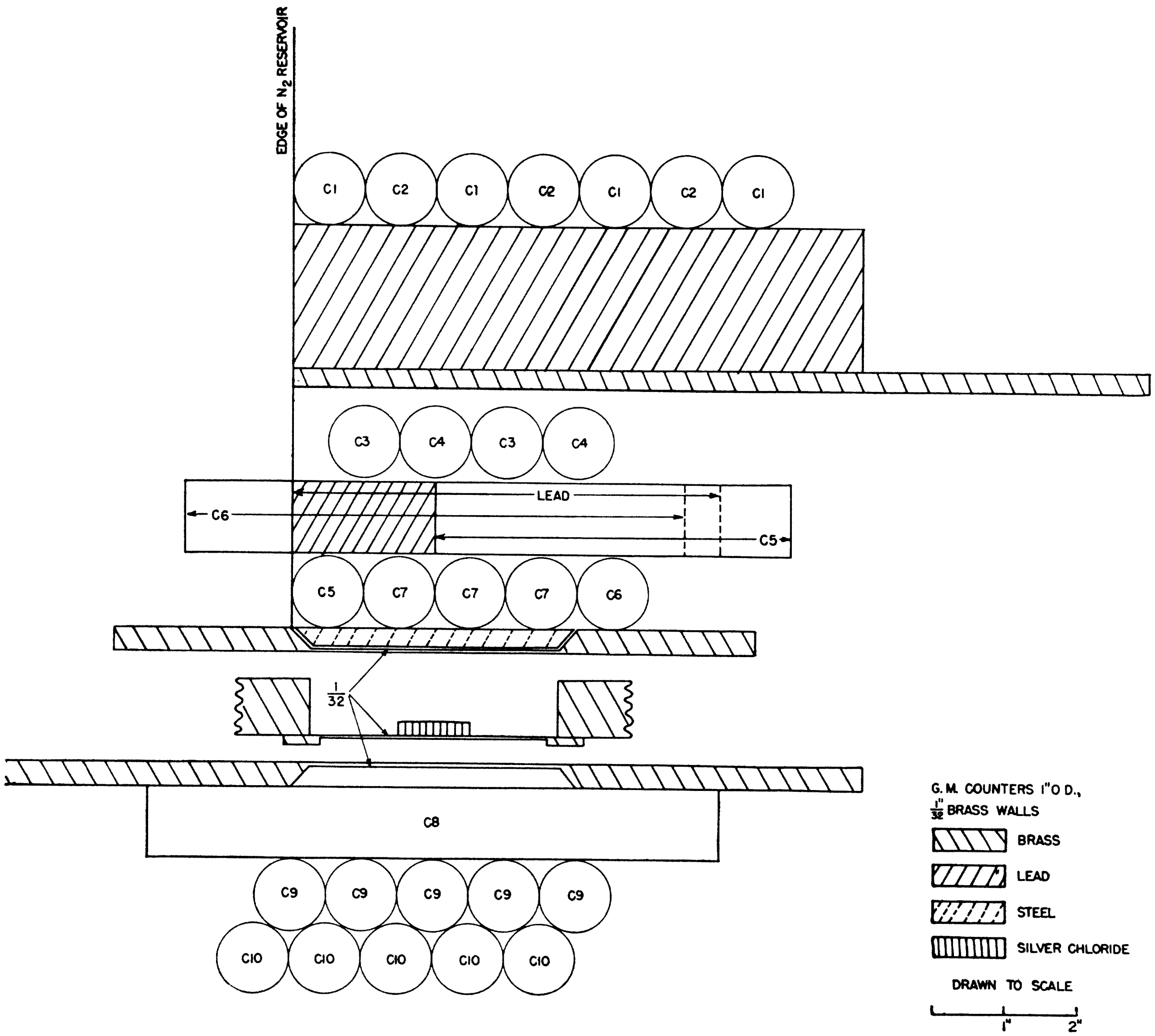

FIG. 2. Counter geometry in the second run.

[9] Continuous wound, 1100 ohm, delay approximately 1 μsec. per ft., J. Millen Company, Malden, Massachusetts.

[10] For the most part the equipment was based on Los Alamos designs, the amplifier due to W. C. Elmore, the precision pulser and coincidence circuit due to M. Sands, and the sweep and discriminator circuits as reported by Fitch and Titterton in Rev. Sci. Inst. **18**, 821 (1947).

[11] Few of the purchased crystals were useful. The crystal used was selected by trial from a large group to have good time and fair amplitude response.

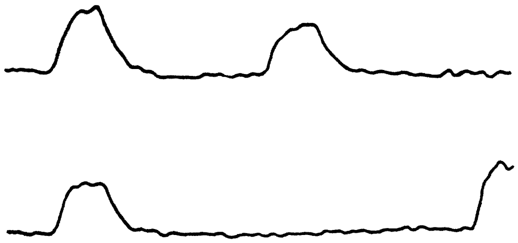

FIG. 3. Meson decay events.

a liquid nitrogen reservoir. The low crystal temperature is required because the crystal is an ionic conductor at room temperature but at 77°K is nearly a perfect insulator.[12]

The data were taken at sea level (Cambridge, Massachusetts) during two runs characterized chiefly by the use of different G-M counters and counter geometry. In the first run two counter trays, A and B, were placed above the crystal, X, and anti-coincidence trays, D, were below X. Four inches of lead above A and B covered the solid angle. The events examined were $(A+B+X-D)$ events, designated as anti-coincidence or AC events. It was found that the number of AC events observed, G(obs), exceeded by a factor of nearly 2 the number of calculated AC events, G(calc),[13] and it was also found that the difference was due chiefly to the presence of side showers. In the second run the effect of side showers was essentially eliminated by using the arrangement of Fig. 2; agreement was obtained between G(obs) and G(calc). In this case in order that the CRT sweep be started, signals must be obtained simultaneously from either $C1$ or $C2$ but not both, either $C3$ or $C4$ but not both, $C7$, and the crystal, but no signal must appear in $C5$, 6, 8, 9, or 10.

III. RELATIVE TIME MEASUREMENTS

The crystal produced pulses with rise times at the CRT of 0.2 to 0.35 μ sec. A few pulses had either longer or shorter rise times. Examples of crystal pulses are given in Fig. 3. It is estimated that relative times, i.e., times between crystal pulses, can be measured with an accuracy of 0.03 μsec. (s.d.), provided the pulses do not overlap.

A number of mesons which stopped in the crystal were observed to decay. Figure 3 shows two of the events. The initial pulse was produced by the meson and the second pulse by the decay electron. We can make a statistical check on the crystal's time measuring properties by determining the mean life τ of positive mesons,[14] using the individual measured life times. During an operating period of 950 hours (the first and second runs combined), 79 mesons with life times in the range 1.00 to 5.50 μsec., inclusive, were observed to decay. (The CRT sweep length was about 6.0 μsec.) Using a method developed by Peierls,[15] τ is calculated to be 1.9 ± 0.3 (s.d.) μsec. The presently accepted value is 2.15 ± 0.07 μsec. The only important error in τ is the statistical one, and it is large because only a relatively few (79) decays are measured.

Figure 4 shows the integral decay time curve. It has been corrected for eight decay events which, it is calculated, were missed because of the short sweep length.

IV. STAR PRODUCTION AND AMPLITUDE RESPONSE

As the initial step in the first run, a flux curve, Fig. 5, was measured. We define the flux as the number of particles per min. traversing the crystal and lying within the solid angle defined by the counters. (For a flux measurement the AC counters are disconnected.) The measured flux F is a function of the amplitude discriminator setting D; the flux curve, which is actually an integral pulse height curve, gives the relation between the two. Most of the particles which contribute to F are high energy mesons which ionize at or near the minimum rate. Even if all mesons ionized at the same average rate, all pulses would not have the same amplitude because of statistical fluctuations in ionization.[16] This fact together with the distribution of the meson zenith angles can be shown to explain the shape of the flux curve.

From the flux curve we estimate that the total flux, F(obs), is 4.5 ± 0.4 particles/min., corresponding to $D=20$. (The curve is probably influenced appreciably by noise for smaller D values.) We calculate that 4.7 ± 0.5 particles/min. $=F$(calc) and conclude that the crystal detected most of the fast particles which passed through it.[13]

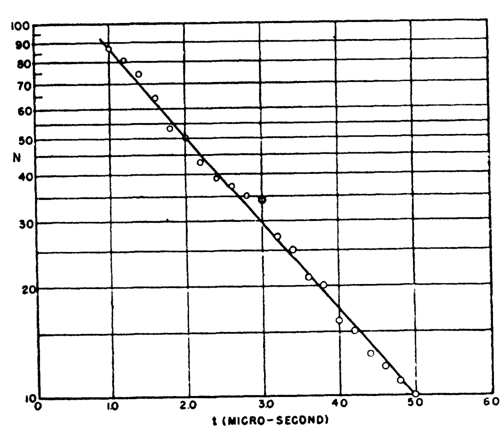

FIG. 4. Integral decay time curve.

[12] Mott and Gurney, *Electronic Processes in Ionic Crystals* (Oxford University Press, London, 1941).

[13] F and G are calculated using data given by B. Rossi, Rev. Mod. Phys. **20**, 537 (1948). The authors are indebted to W. L. Kraushaar for information concerning the angular distribution of slow mesons at sea level.

[14] That practically none of the negative mesons decay in AgCl is inferred from the results of Conversi, Pancini, and Piccioni and others, Phys. Rev. **68**, 232 (1945) and **71**, 209 (1947).

[15] R. Peierls, Proc. Royal Soc. **149**, 467 (1935).

[16] K. Symon, thesis, Harvard University, 1948.

From K. Symon's theory of energy loss fluctuations[16] and the analysis of the shape of the flux curve, we find that the knee of the flux curve, which is at 210 μvolts, corresponds to a particle energy loss in the crystal of 3.7 Mev, or that the signal-energy loss conversion ratio C_E is 56 μvolts/Mev. We use this value of C_E together with a value of 7.0 ev per conduction electron (the average energy required to liberate one conduction electron[1, 8]) to calculate the mean path, w, of conduction electrons in the crystal. The calculation is made according to a simple procedure described by Mott and Gurney (page 117),[12] and we obtain $w=0.064$ cm, or one-tenth the crystal thickness. Due to the small value of w the pulse height is almost exactly proportional to particle energy loss in the crystal. Thus, the pulse height is relatively independent of the point in the crystal at which conduction electrons are released.

With the AC counters connected, $4.6\pm0.4=G(\text{obs})$ particles/hr were observed to stop for a typical set of operating conditions in the first run. It was calculated that $1.7\pm0.2=G(\text{calc})$ mesons/hr should stop. As explained previously the discrepancy is chiefly due to side showers. A detailed analysis of the pulse heights for stopped particles is very difficult in the first run because of the effect of side showers and because the first run was really a preliminary run, and consequently changes were made from time to time in the operating conditions. However, a rough check on the crystal's amplitude response is obtained using the largest pulses only. Fifteen percent (or 9) of the mesons which stopped and were observed to decay produced pulses larger than 900 μvolts, the average pulse height being 1100 μvolts and the maximum 1400 μvolts. These large pulses must have been produced by mesons which stopped at or near the bottom of the crystal, i.e., by mesons which lost a maximum amount of energy in the crystal. Using the angular distribution of slow mesons[13] and a calculated range *versus* energy $(R-E)$ curve for mesons in AgCl,[17] we calculate that the "average" maximum energy loss of a meson which stops in the crystal is 17.5 Mev. The "average" is taken over the 15 percent of particles with angles and ranges chosen to give the largest pulses. The corresponding pulse height is, therefore, $56\times17.4=1000$ μvolts, to be compared with the observed value of 1100 μvolts.

A second rough qualitative check on amplitude response exists because find that the slow mesons which stopped (the ones observed to decay) produced a set of pulses significantly larger in amplitude than the pulses in the set produced by fast mesons, i.e., the pulses of the flux curve.

The second run was started one month after the end of the first run. The flux curve given in Fig. 5 indicates that the crystal properties were different in the second run; a plateau is barely in evidence, and a knee is perhaps discernible at 120 μvolts ($D=20$), which would make $C_E=32$ μvolts/Mev, but the existence and position of the knee are too indefinite to permit a good calculation of C_E. However, using $C_E=56$ μvolts/Mev from the first run and considering the whole of the flux curves for both runs, we can establish that C_E for the second run is about 44 μvolts/Mev. The reason for the crystal change is uncertain.[18] It was possible, however, in the second run to obtain useful information about the crystal properties and about star production.

A value for the total flux $F(\text{obs})$ is not obvious from examination of the flux curve. $F(\text{obs})=4.6$ particles/min. is probably the lower limit. $F(\text{calc})$ is found to be 5.4 ± 0.5 particles/min., i.e., $F(\text{obs})$ is smaller than $F(\text{calc})$ by 15 percent. We can conclude that also in the second run the crystal detected most of the fast particles which passed through it.

In the second run with the discriminator set to accept pulses larger than approximately 180 μvolts, 301 particles stopped in 320.5 hours. An additional number (18) of positive mesons which stopped were not observed because they decayed with life times less than 0.7 μsec., and the decay electrons discharged the AC

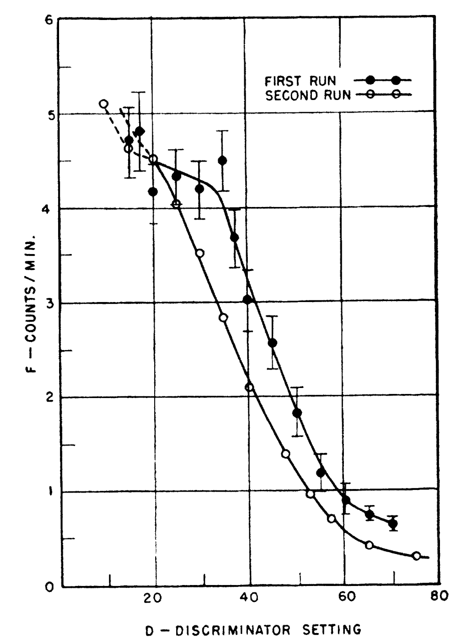

FIG. 5. Flux curves.

counters. (In order to allow for spontaneous lags in the discharge of the AC counters, the circuits excluded events in which the AC counters discharged within 0.7 μsec. following a complete set of coincidence pulses.) Thus, $G(\text{obs})=1.00\pm0.06$ particles/hr whereas $G(\text{calc})=1.1\pm0.2$ stopped mesons/hr. The observed integral pulse height distribution is given in Fig. 6. Five pulses have amplitudes greater than 1200 μvolts;

[17] H. G. Voorhies, Thesis (Harvard University, 1949).

[18] Checks on the crystal flux rate indicated that the crystal properties remained essentially constant during each run.

three at about 1500, one at 2000, and one at 3000. Forty of the pulses can be identified as positive meson pulses because they are accompanied by a delayed pulse. The integral distribution for the 40 is given also in Fig. 6. The 40 pulse heights lie between 200 and 1200 μ-volts.

For purposes of analysis consider two groups of pulses. Let all pulses larger than 200 μvolts (produced by stopped particles) constitute group A; let the 40 pulses produced by stopped positive mesons observed to decay constitute group B. Thus, group B, which forms part of group A, contains only positive meson pulses; group A contains pulses produced by both positive and negative mesons as well as other possible particles. The 12 percent of the pulses with amplitudes less than 200 μvolts are excluded from group A because these small pulses are probably not meson pulses in view of the group B distribution. (The exclusion of these makes $G(\text{obs})=0.9\pm0.07$ stopped mesons/hr.) Probably AC counter inefficiency accounts for most of the small pulses. An inefficiency of only 0.05 percent is necessary to account for all of the 12 percent.

The particles we are considering stopped either in the crystal or the brass which separates the bottom of the crystal from the active volume of the AC counters. The crystal represents 0.635 cm of AgCl stopping material and the brass 0.508 cm of AgCl equivalent stopping material. We now calculate the expected numerical distribution of mesons in the stopping material. Relative stopping powers of the AgCl and brass chiefly determine the distribution for group A. For group B the distribution is determined both by the relative stopping powers and by the detection efficiency for decay electrons originating in the crystal and brass.[19] A summary of the expected numerical distribution[20] is given in

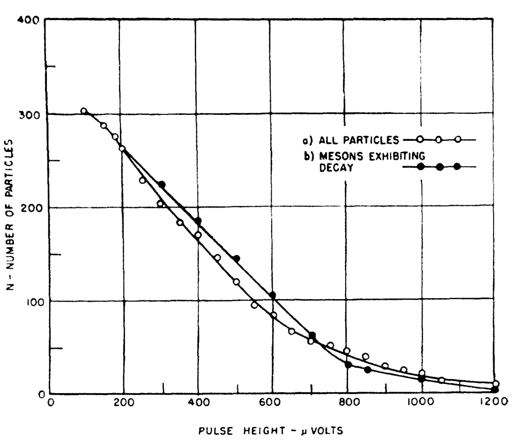

FIG. 6. Integral pulse height curves for stopped particles in the second run. Curve b is normalized to curve a at 200 μvolts.

TABLE I. Expected distribution of mesons in stopping material for the second run.

Material	Group A		Group B
Crystal	147 (±)	78 (−), 56%	28 (+), 70%
		69 (+)	
Brass	116 (±)	, 44%	12 (+), 30%

Table I. The important thing to notice is that 78 of the pulses of group A have the possibility of modification by star particles because the pulses are due to negative mesons which stopped in the crystal, whereas none of the pulses of group B can be affected by star particles. We assume that stars are detected only if they originate in the crystal. If for the moment we exclude from group A the five pulses exceeding 1200 μvolts, then for group A only 10 percent (or 26) of the pulses exceed 1000 μvolts, and only 3 percent (7) are 1200 μvolts; in group B, 7 percent (3) exceed 1000 μvolts, and 3 percent (1) are 1200 μvolts. Thus, except for five pulses in group A larger than 1200 μvolts, the relative numbers of large pulses in the two groups are about the same. If a negative meson stopped in the crystal and produced a star in which the charged particles carried on the average approximately half the meson rest energy, a pulse exceeding 2000 μvolts would result. It is evident from our data that this star process occurs rarely or not at all. The five pulses of group A with amplitudes exceeding 1200 μvolts could be produced by protons since the average pulse of a stopped proton would be about 1400 μvolts and the maximum pulse about 2500 or 3000 μvolts.[21] We cannot, however, exclude the possibility that these 5 pulses are star pulses.

We now examine our data for the presence of weak stars. Let V_A and V_B be the average pulse sizes for groups A and B, respectively. $V_A=527$ μvolts, and $V_B=546$ μvolts, where a small (2 percent) correction has been made to V_A for possible meson-decay electron overlap. In order to determine the reliability of V_A and V_B we assume that the pulse height distributions of Fig. 6 are Gaussian. This is only approximately true but will give us a first order estimate of errors. We find that $V_A=527\pm15$ (s.d.) μ-volts, and $V_B=546\pm35$ μvolts. Let V_T be the average pulse height for mesons which stop uniformly in depth in the crystal and brass and which produce no stars. Thus, V_T is essentially the average pulse height obtained for group A when the effects of stars are subtracted. V_T would equal V_A if no star production occurred. Let V_S be the average contribution to pulses due to stars originating in the crystal. Then,

$$V_T=(263V_A-78V_S)/263. \qquad (1)$$

[19] The detection efficiency ϵ cannot be calculated accurately. For example, ϵ(obs) is 0.29 ± 0.08 and ϵ(calc) is 0.40 ± 0.10.

[20] We assume that equal numbers of positive and negative mesons stop. The excess of negatives expected to stop in the crystal exists because decay electrons from positive mesons with short life times can discharge the AC counters and, thus, exclude the mesons from observation, as explained previously.

[21] As is shown later, the average pulse height for stopped mesons is about 525 μvolts. From the R-E curves we find that, approximately, the average pulse height for stopped protons is 2.6 times the average meson pulse height.

In our experiment the ratio V_T/V_B, designated as k, has a particular value determined by the distribution of stopping material and the detection efficiencies for decay electrons originating at various points in the stopping material. We write,

$$V_T = kV_B. \tag{2}$$

Substituting in Eq. (1) for V_T, using Eq. (2), we find

$$V_S = 3.37(V_A - kV_B),$$

or

$$V_S = 3.37(527 - k546) \pm 128\ \mu\text{volts}. \tag{3}$$

The ratio k of the average pulse height for mesons stopping uniformly in depth in the crystal and brass with no star production to the average pulse height for mesons observed to decay is determined in the following manner. Using the $R-E$ curve for AgCl, we calculate a set of relative pulse height curves for mesons which stop in the crystal and brass. Relative pulse height Y is plotted *versus* range R in the stopping material with zenith angle as a parameter. For a meson with range R in the stopping material,

$$Y(R) = \text{const. } \Delta E, \tag{4}$$

where ΔE is the energy loss of the meson in the crystal. Equation (4) is a consequence of the fact that the mean path of conduction electrons is short relative to the crystal thickness. Using the relative pulse height curves and estimates of the detection efficiency for decay electrons from mesons with various ranges in the stopping material, we calculate relative pulse heights for V_T and V_B and find that $k = 1.07$. Consequently, $V_S = -193 \pm 128\ \mu$volts.

In order to express V_S in units of energy we must know C_E, the signal-energy loss conversion ratio. We can check the value $C_E = 44\ \mu$volts, obtained previously, by determining C_E by another method. We calculate the average energy $\langle \Delta E \rangle$ lost in the crystal by mesons which stop uniformly in the crystal and brass, i.e., the mesons of group A (with no star production). $\langle \Delta E \rangle = 12.2$ Mev. The average pulse height for such mesons is given approximately by $V_T = 1.07 \times 546 = 584$ μvolts. Thus, $C_E = 48\ \mu$volts/Mev. Using an average value, $C_E = 46\ \mu$volts/Mev, we obtain for the average size of star pulses

$$V_S = -4 \pm 3 \text{ Mev}.$$

It is difficult to estimate the error introduced in the calculation of k. We might best consider two extreme cases. For case (a), we assume that mesons of group B stopped uniformly in the crystal and the brass, i.e., that the detection efficiency ϵ of decay electrons is unity for mesons stopping both in the crystal and in the brass, We then find that $k = 1.0$ and $V_S = -1.4 \pm 2.8$ Mev. For case (b), we assume that mesons of group B stopped uniformly in the crystal and none stopped in the brass, i.e., $\epsilon = 1$ in the crystal and $\epsilon = 0$ in the brass. We find that $k = 1.25$ and $V_S = -12 \pm 2.8$ Mev.

From our results we conclude that probably no stars are produced by nuclear capture of negative μ-mesons and that if stars are produced, the average energy of the charged particles is but a very few Mev, probably less than 3 Mev.

If no star production occurs, then V_T is given very closely by V_A, or $527 \pm 15\ \mu$volts; therefore,

$$C_E = 527/12.2 = 43\ \mu\text{volts/Mev}.$$

This value is somewhat high in comparison with 32 μvolts/Mev from the knee of the flux curve but in good agreement with the value 44 μvolts/Mev obtained from comparison of the first and second flux curves as a whole. We observe that the value 43 μvolts/Mev for C_E has been obtained using experimental data for slow, heavily ionizing mesons and agrees with the value 44 μvolts/Mev obtained using data of the flux curves for fast, lightly ionizing mesons.

V. ACKNOWLEDGMENTS

One of the authors (H.G.V.) would like to express his appreciation to the Shell Oil Company for a fellowship given to him during the course of the work described in this paper. Both of us would like to thank Professor Matthew L. Sands for his helpful assistance on several occasions.